

Fermion Masses and Leptogenesis from The Left-Right Symmetric Model

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Abstract: The paper suggests a left-right mirror symmetric model with the flavor symmetries $Z_{3L} \otimes Z_{3R}$. It can simultaneously accommodate the standard model, neutrino physics and the baryon asymmetry. The fermion masses and CP violation originate from vacuum spontaneous breaking of the flavor field. The baryon asymmetry is implemented through the leptogenesis which is related to the lepton CP violation. The model can naturally and correctly reproduce all kinds of experimental data, in particular, all of the values of the fermion masses and mixings are accurately fitted by the fewer parameters. Finally, it is also feasible and promising to test the model in future experiments.

Keywords: left-right symmetric model; fermion mass and mixing; leptogenesis

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I. Introduction

The standard model (SM) has been evidenced to be a correct theory at the electroweak scale, but it also contains some flaws [1]. The left-handed and right-handed fermions belong to the asymmetric gauge group representations. The Yukawa couplings have too large freedoms in view of the lack of a flavor symmetry, as a result, the fermion masses and mixings are apparently in confusion, and the origin of the CP violations is still unknown, this is namely so-called flavor puzzle [2]. On the other hand, the SM can not account for such issues as the light neutrino masses [3], the baryon asymmetry [4], the cold dark matter [5], etc. Therefore, the SM should only be regarded as a low-energy effective theory, there must be a more full and fundamental theory beyond the SM, which is ultimately in charge of the matter origin in the early universe evolution.

In the last few decades, all the time all kinds of theoretical ideas have been suggested to solve the above-mentioned issues. The left-right mirror symmetry is a well-motivated idea because it meets the aesthetics. The left-right symmetric model is pioneered by Pati and Salam in [6], later is developed by the authors in [7]. This type of model can be derived from the GUT and have many advantages, so they have been extensively studied [8]. Recently, the researches of the flavor symmetry attract great attentions in view of it succeeding in the neutrino mass and mixing [9]. The flavor symmetry is surely relevant to the origin of the fermion masses and CP violation, this connection has been discussed in a lot of references [10]. The baryon asymmetry through the leptogenesis is also a successful idea [11], many progresses have been made in this field [12]. These ideas are all insights and can be considered as approaches to a new theory. However, the new theory should in line with the early universe harmony and the nature unification. Therefore, a realistic theory should simultaneously accommodate the SM, neutrino physics and the baryon asymmetry, moreover, it can account for the origin of the fermion masses and CP violation, in other words, the flavor symmetry has to be integrated into it. Undoubtedly, exploring such theoretical model is very significant for particle physics as well as cosmology.

In this work, I suggest a left-right symmetric model. The model has the local gauge groups $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ and the flavor symmetries $Z_{3L} \otimes Z_{3R}$. Besides the SM particles, some new particles are introduced in the model. The model symmetries and their breakings lead to a special effective Yukawa couplings at the low energy, essentially, the fermion masses and mixings and the CP violations originate from vacuum spontaneous breaking of the flavor field. The generated quark and lepton mass matrices are not independent but rather interrelated. In addition, the baryon asymmetry is successfully implemented through the leptogenesis, which is closely related to the lepton CP violation. The model can correctly reproduce all kinds of the observed data of the SM, neutrino physics and the baryon asymmetry, in particular, all of the values of the fermion masses and mixings are accurately fitted by the fewer parameters. Finally, the model is feasible and promising to be tested in future experiments.

The remainder of this paper is organized as follows. In Section II I outline the model and discuss the fermion mass generations. Sec. III I introduce the leptogenesis in the model. The numerical results are given in Sec. IV. Sec. V is devoted to conclusions.

II. Model

The gauge symmetries of the model are the left-right symmetric local groups $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$. The model particle contents and their gauge quantum numbers are in detail listed as follows,

$$\begin{aligned} & G_\mu(8, 1, 1, 0), \quad W_{L\mu}(1, 3, 1, 0), \quad W_{R\mu}(1, 1, 3, 0), \quad X_\mu(1, 1, 1, 1), \\ & [\Phi_L, q_L](3, 2, 1, \frac{1}{3}), \quad [\Phi_R, q_R](3, 1, 2, \frac{1}{3}), \quad [H_L, l_L](1, 2, 1, -1), \quad [H_R, l_R](1, 1, 2, -1), \\ & \phi_c(3, 1, 1, -\frac{2}{3}), \quad \phi^-(1, 1, 1, -2), \quad [N_L, N_R](1, 1, 1, 0), \quad F(1, 1, 1, 0), \end{aligned} \quad (1)$$

where all kinds of the fermions imply three generations as usual. H_L and H_R are respectively the left-handed and right-handed isospin doublet scalars, while Φ_L and Φ_R are scalars which belong to both color triplet and isospin doublet. N_L and N_R are singlet Majorana fermions. F is a singlet scalar flavor field, which is a 3×3 matrix in the flavor space. The other notations are self-explanatory. In addition to the gauge symmetries, the model has an attractive left-right mirror symmetry. It is characterized by the field transforms as follows,

$$W_{L\mu} \leftrightarrow W_{R\mu}, \quad \Phi_L/H_L \leftrightarrow \Phi_R/H_R, \quad q_L/l_L/N_L \leftrightarrow q_R/l_R/N_R, \quad F \leftrightarrow F^\dagger, \quad (2)$$

where the mirror particles of $G_\mu, X_\mu, \phi_c, \phi^-$ are exactly themselves. Lastly, the model has the flavor symmetries $Z_{3L} \otimes Z_{3R}$, which are three order cyclic groups for three generations of the left-handed and right-handed fermions, respectively. The above-mentioned symmetries are simple and natural, they are the theoretical basis of the model.

The model Lagrangian is easy written out on the basis of the symmetries and particle contents. The gauge kinetic energy terms are

$$\begin{aligned} \mathcal{L}_{Gauge} = & \mathcal{L}_{pure\ gauge} + i\bar{f}_L\gamma^\mu D_\mu f_L + i\bar{f}_R\gamma^\mu D_\mu f_R \\ & + (D^\mu\Phi_L)^\dagger D_\mu\Phi_L + (D^\mu\Phi_R)^\dagger D_\mu\Phi_R + (D^\mu H_L)^\dagger D_\mu H_L + (D^\mu H_R)^\dagger D_\mu H_R \\ & + (D^\mu\phi_c)^\dagger D_\mu\phi_c + (D^\mu\phi^-)^\dagger D_\mu\phi^- + Tr[\partial^\mu F^\dagger \partial_\mu F], \end{aligned} \quad (3)$$

where f_L, f_R denote the left-handed and right-handed fermions, and the covariant derivative D_μ is defined by

$$D_\mu = \partial_\mu + i \left(g_s G_\mu^a \frac{\lambda^a}{2} + g_w W_{L\mu}^i \frac{\tau_L^i}{2} + g_w W_{R\mu}^i \frac{\tau_R^i}{2} + g_x X_\mu \frac{B-L}{2} \right). \quad (4)$$

g_s, g_w, g_x are three gauge coupling parameters. λ^a and τ^i are respectively the Gell-Mann and Pauli matrices. $B-L$ is the charge operator of $U(1)_{B-L}$, namely the baryon number minus the lepton one.

The model Yukawa couplings are

$$\begin{aligned}
\mathcal{L}_{Yukawa} = & H_L^\dagger N_L^T C Y_1 l_L + \Phi_L^\dagger N_L^T C Y_2 q_L + \phi_c^\dagger l_L^T C Y_3 i\tau_2 q_L + \frac{1}{2} \phi^+ l_L^T C Y_4 i\tau_2 l_L \\
& + H_R^\dagger N_R^T C Y_1 l_R + \Phi_R^\dagger N_R^T C Y_2 q_R + \phi_c^\dagger l_R^T C Y_3 i\tau_2 q_R + \frac{1}{2} \phi^+ l_R^T C Y_4 i\tau_2 l_R \\
& - \frac{1}{2} N_L^T C M_N N_L - \frac{1}{2} N_R^T C M_N N_R - \overline{N}_L Y_5^\dagger F Y_5 N_R + h.c., \tag{5}
\end{aligned}$$

where C is a charge conjugation matrix, $i\tau_2$ is inserted in order to satisfy the $SU(2)$ isospin symmetries. The left-right mirror symmetry is very evident. The model flavor symmetries are characterized by $Z_{3L} \otimes Z_{3R}$ as follows,

$$\begin{aligned}
T &= \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \quad T^2 = T^{-1} = T^T, \quad T^3 = I, \quad T^T Y_k T = Y_k, \\
Y_k &= a_k T + b_k T^T + c_k I, \quad M_N = \overline{M}_N (T + T^T + c_N I) = \overline{M}_N Y_N, \\
F &= U_{FL} \text{diag}(F_1, F_2, F_3) U_{FR}^\dagger, \\
f_L &\longrightarrow T_L f_L, \quad f_R \longrightarrow T_R f_R, \quad F \longrightarrow T_L F T_R^T, \tag{6}
\end{aligned}$$

where $k = 1, 2, 3, 4, 5$. T is the generator of Z_3 and I is an unit matrix. Y_k and M_N have simple structures and fewer parameters by virtue of the flavor symmetries. all of the coefficients, a_k, b_k, c_k, c_N , are required to be real numbers, so the CP invariance is also satisfied. Y_4 is an antisymmetric matrix on account of $\tau_2^T = -\tau_2$, so $a_4 = -b_4, c_4 = 0$. Y_N is a symmetric matrix. \overline{M}_N should be the GUT scale, namely $\overline{M}_N \sim 10^{15}$ GeV. The flavor field F is parameterized by three complex scalar fields and two dimensionless unitary flavor fields. The left-handed and right-handed fermions are independently transformed according to the separate group Z_{3L} and Z_{3R} , so there are not directly couplings of the left-handed fermions to the right-handed ones except the last term in (5), which is the only link between the left-handed fermions and the right-handed ones. These characteristics of the Yukawa couplings will result in a new mechanism by which the fermion masses and mixings and the CP violation are generated.

The model scalar potentials are given by

$$\begin{aligned}
V_{Scalar} = & \lambda_H \left(H_L^\dagger H_L - \frac{\lambda_H v_L^2 + \lambda_1 v_R^2}{2\lambda_H} \right)^2 + \lambda_H \left(H_R^\dagger H_R - \frac{\lambda_H v_R^2 + \lambda_1 v_L^2}{2\lambda_H} \right)^2 \\
& + \lambda_F (Tr[F^\dagger F] - v_F^2)^2 + \lambda_\Phi (\Phi_L^\dagger \Phi_L)^2 + \lambda_\Phi (\Phi_R^\dagger \Phi_R)^2 + \lambda_{\phi_c} (\phi_c^\dagger \phi_c)^2 + \lambda_{\phi^-} (\phi^+ \phi^-)^2 \\
& + 2\lambda_1 H_L^\dagger H_L H_R^\dagger H_R + 2(H_L^\dagger H_L + H_R^\dagger H_R)(\lambda_2 \Phi_L^\dagger \Phi_L + \lambda_2 \Phi_R^\dagger \Phi_R + \lambda_3 \phi_c^\dagger \phi_c + \lambda_4 \phi^+ \phi^-) \\
& + \lambda_5 (\Phi_L^\dagger H_L H_R^\dagger \Phi_R + h.c.) + \lambda_6 (\Phi_L^\dagger \tilde{H}_L \tilde{H}_R^\dagger \Phi_R + h.c.) \\
& + \text{other weak coupling terms}, \tag{7}
\end{aligned}$$

where $\tilde{H}_L = -i\tau_2 H_L^*$ and $\tilde{H}_R^\dagger = H_R^T i\tau_2$. All of the self-coupling parameters, $\lambda_H, \lambda_F, \lambda_\Phi, \lambda_{\phi_c}, \lambda_{\phi^-}$, are positive and should be ~ 0.1 , while the interactive couplings, $\lambda_1, \lambda_2, \dots, \lambda_6$, are weak

and should be < 0.1 . v_L and v_R are respectively the vacuum expectation values (VEVs) of H_L and H_R . The potential vacuum configurations are as follows,

$$\begin{aligned}\langle H_L \rangle &= \frac{v_L}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \langle H_R \rangle = \frac{v_R}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \\ \langle F \rangle &= v_F \text{diag} (\cos\alpha\cos\beta e^{i\delta_1}, \cos\alpha\sin\beta e^{i\delta_2}, \sin\alpha e^{i\delta_3}) = v_F Y_F,\end{aligned}\tag{8}$$

where $\langle F \rangle$ is derived from the three complex scalar breakings. Explicitly, $v_L \neq v_R \neq 0$ will spontaneously break the gauge symmetries and the left-right mirror symmetry, on the other hand, $v_F \neq 0$ will spontaneously break the flavor symmetries, simultaneously, the CP invariance will spontaneously be broken due to the non-vanishing and irremovable phases in $\langle F \rangle$. However, the symmetry breaking sequence is controlled by the hierarchy of the VEVs such as $v_L \sim 10^2 \ll v_R \sim 10^{13} < v_F \sim 10^{15}$ (in GeV as unit). Firstly, the flavor symmetries are broken and CP is violated at the scale v_F . Secondly, at the scale v_R $SU(2)_R \otimes U(1)_{B-L}$ is broken down $U(1)_Y$ which is namely the hypercharge subgroup of the SM, at the same time the left-right mirror symmetry is lost. Lastly, $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$ is completed at the scale v_L , i.e. the electroweak breaking. These symmetry breakings are accomplished step by step in the universe evolution.

The breaking of the flavor symmetries directly generates the Dirac mass of the Majorana fermions N_L and N_R as follows,

$$M_{ND} = v_F Y_5^\dagger Y_F Y_5 = v_F Y_{ND}.\tag{9}$$

The Dirac mass term is the only source of the flavor breaking and CP violation, and it will play a key role in origin of masses and mixings of the quarks and leptons.

After the gauge symmetries are broken, the masses and mixings of the scalar and gauge bosons are easily derived by the standard program. The detailed expressions are as follows,

$$\begin{aligned}M_{H_L} &= \sqrt{2\lambda_H} v_L, \quad M_{H_R} = \sqrt{2\lambda_H} v_R, \\ M_{\Phi_{L,R}} &= \sqrt{\lambda_2(v_L^2 + v_R^2)}, \quad M_{\phi_c} = \sqrt{\lambda_3(v_L^2 + v_R^2)}, \quad M_{\phi^-} = \sqrt{\lambda_4(v_L^2 + v_R^2)}, \\ M_{W_L} &= \frac{g_w v_L}{2}, \quad M_{Z_L} = \frac{M_{W_L}}{\cos\theta_W}, \quad M_{W_R} = \frac{g_w v_R}{2}, \quad M_{Z_R} = \frac{M_{W_R}}{\cos\theta'_W}, \\ \tan\theta'_W &= \frac{g_x}{g_w}, \quad \tan\theta_W = \frac{g_Y}{g_w} = \sin\theta'_W, \quad Q_e = I_3^L + I_3^R + \frac{B-L}{2},\end{aligned}\tag{10}$$

where θ'_W and θ_W are the mixing angles of the neutral gauge fields for the $SU(2)_R$ breaking and the $SU(2)_L$ one, respectively. However, the mixings between the left-type bosons and the right-type ones are negligible since $v_L \ll v_R$. Obviously, the non-SM particles in (10) have super-heavy masses close to the scale v_R .

On the basis of the model Lagrangian and symmetry breakings, the fermion masses and mixings are generated by the following mechanism. First of all, the super-heavy Majorana fermions N_L and N_R are decoupling below the scale v_F , so we can integrate them out and

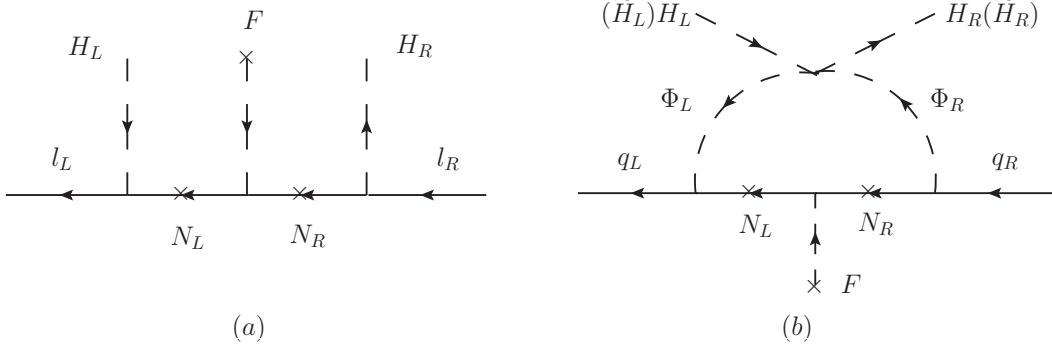


Figure. 1. The generations of the fermion Dirac couplings, (a) for the neutrinos, (b) for the up-type and down-type quarks.

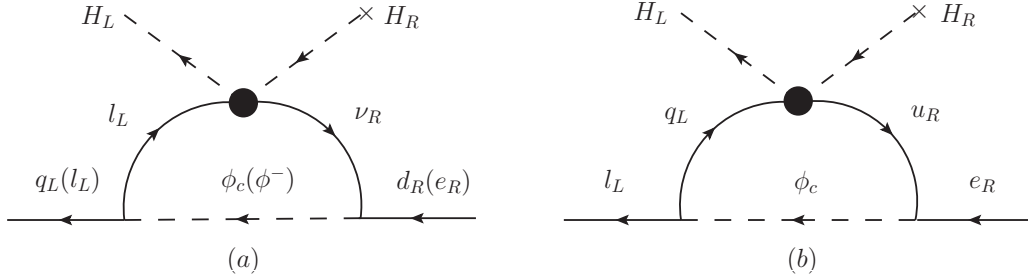


Figure. 2. The generations of the fermion Dirac couplings, (a) for the down-type quarks and the charged leptons, (b) for the charged leptons.

derive three types of the effective Yukawa couplings, i) the respective Majorana coupling of l_L and l_R , ii) the Dirac coupling of l_L and l_R , iii) two Dirac couplings of q_L and q_R . The neutrino Dirac coupling is generated by (a) in Figure 1, and (b) in Figure 1 can generate the up-type quark coupling and the down-type one, which are respectively related to H_L, H_R and \tilde{H}_L, \tilde{H}_R . These effective couplings will give the neutrino and quark masses after H_L and H_R developing the VEVs. Secondly, we can put together the neutrino Dirac coupling and the Yukawa couplings involving ϕ_c and ϕ^- , thus a new down-type quark coupling and a charged lepton coupling are generated by (a) in Figure 2. we can also make use of the up-type quark coupling and the Yukawa coupling involving ϕ_c to generate the other charged lepton coupling by (b) in Figure 2. The black dots in Figure 2 namely denote the corresponding effective couplings in Figure 1. To sum up, the complete

effective Yukawa couplings are given by

$$\begin{aligned}
\mathcal{L}_{Yukawa}^{eff} = & \frac{1}{2\overline{M}_N} \overline{l}_L H_L Y_1^\dagger Y_N^{*-1} Y_1^* H_L^T C \overline{l}_L^T + \frac{1}{2\overline{M}_N} l_R^T C H_R^* Y_1^T Y_N^{-1} Y_1 H_R^\dagger l_R \\
& - \frac{v_F}{\overline{M}_N^2} \overline{l}_L H_L Y_1^\dagger Y_N^{*-1} Y_{ND} Y_N^{-1} Y_1 H_R^\dagger l_R + \frac{\lambda_5 B_0 v_F}{16\pi^2 \overline{M}_N^2} \overline{q}_L H_L Y_2^\dagger Y_N^{*-1} Y_{ND} Y_N^{-1} Y_2 H_R^\dagger q_R \\
& + \frac{\lambda_6 B_0 v_F}{16\pi^2 \overline{M}_N^2} \overline{q}_L \tilde{H}_L Y_2^\dagger Y_N^{*-1} Y_{ND} Y_N^{-1} Y_2 \tilde{H}_R^\dagger q_R + \frac{\sqrt{2}}{16\pi^2 v_R} \overline{q}_L \tilde{H}_L Y_3^\dagger (A_{\alpha\beta} Y_{D\alpha\beta}^*) Y_3 \tilde{H}_R^\dagger q_R \\
& + \frac{\sqrt{2}}{16\pi^2 v_R} \overline{l}_L \tilde{H}_L Y_4^\dagger (B_{\alpha\beta} Y_{D\alpha\beta}^*) Y_4 \tilde{H}_R^\dagger l_R + \frac{\sqrt{2}}{16\pi^2 v_R} \overline{l}_L \tilde{H}_L Y_3^* (C_{\alpha\beta} Y_{u\alpha\beta}^*) Y_3^T \tilde{H}_R^\dagger l_R,
\end{aligned} \tag{11}$$

where Y_D and Y_u are respectively the effective couplings of the neutrinos and the up-type quarks, which are directly derived from the second line of (11), see the following (13). In (11), all kinds of the loop integration factors are eventually simplified by the two-point functions as follows,

$$\begin{aligned}
B_0 &= B_0(M_{H_L}^2, M_{\Phi_L}^2, M_{\Phi_R}^2), \\
A_{\alpha\beta} &= B_0(M_{H_L}^2, m_{\nu_{L\alpha}}^2, M_{\nu_{R\beta}}^2) - B_0(m_d^2, M_{\nu_{R\beta}}^2, M_{\phi_c}^2) - B_0(m_d^2, m_{\nu_{L\alpha}}^2, M_{\phi_c}^2), \\
B_{\alpha\beta} &= B_0(M_{H_L}^2, m_{\nu_{L\alpha}}^2, M_{\nu_{R\beta}}^2) - B_0(m_e^2, M_{\nu_{R\beta}}^2, M_{\phi_-}^2) - B_0(m_e^2, m_{\nu_{L\alpha}}^2, M_{\phi_-}^2), \\
C_{\alpha\beta} &= B_0(M_{H_L}^2, m_{u_\alpha}^2, m_{u_\beta}^2) - B_0(m_e^2, m_{u_\beta}^2, M_{\phi_c}^2) - B_0(m_e^2, m_{u_\alpha}^2, M_{\phi_c}^2),
\end{aligned} \tag{12}$$

where α, β are the generation indexes, they are not summed in (11).

After the gauge symmetry breakings, (11) finally leads to the lepton and quark masses as follows,

$$\begin{aligned}
M_L &= -\frac{v_L^2}{2\overline{M}_N} Y_1^\dagger Y_N^{*-1} Y_1^*, \quad M_R = -\frac{v_R^2}{2\overline{M}_N} Y_1^T Y_N^{-1} Y_1, \\
M_D &= \frac{v_F v_L v_R}{2\overline{M}_N^2} Y_1^\dagger Y_N^{*-1} Y_{ND} Y_N^{-1} Y_1, \quad M_u = -\frac{\lambda_5 B_0 v_F v_L v_R}{32\pi^2 \overline{M}_N^2} Y_2^\dagger Y_N^{*-1} Y_{ND} Y_N^{-1} Y_2, \\
M_d &= \frac{\lambda_6}{\lambda_5} M_u + \frac{1}{16\pi^2} Y_3^\dagger (A_{\alpha\beta} M_{D\alpha\beta}^*) Y_3, \\
M_e &= \frac{1}{16\pi^2} Y_4^\dagger (B_{\alpha\beta} M_{D\alpha\beta}^*) Y_4 + \frac{1}{16\pi^2} Y_3^* (C_{\alpha\beta} M_{u\alpha\beta}^*) Y_3^T, \\
M_{\nu_L}^{eff} &= M_L - M_D M_R^{-1} M_D^T, \\
Y_{f=D,u,d,e} &= -\frac{\sqrt{2}}{v_L} M_f,
\end{aligned} \tag{13}$$

where the effective mass of the left-handed neutrinos is implemented by the see-saw mechanism [13], in addition, the effective Yukawa couplings at the electroweak scale are related to the fermion masses by the last equation in (13). This set of equations of (13) clearly shows the origin of the fermion masses and the interrelations among them. The neutrino

Majorana masses are derived from the coupling Y_N . If the flavor symmetries are unbroken, the Dirac coupling Y_{ND} is vanishing, then the Dirac masses $M_{f=D,u,d,e}$ are all nought. Therefore, Y_N and Y_{ND} are respectively the roots of the Majorana and Dirac masses, all kinds of the fermion masses stem from them, in particular, Y_{ND} is the only source of the flavor symmetry breaking and the CP violation.

For fitting the experimental data, the system of equations (13) are very difficult to be solved. As has been noted early, M_L, M_R, M_D, M_u are all symmetric matrices, in addition, M_L, M_R can be diagonalized by the following unitary matrix U_0 owing to the flavor symmetries but two of the eigenvalues are degenerate. However, we can choose the flavor basis such that M_D and M_u are diagonal matrices simultaneously, then solving becomes relatively easy. Lastly, Y_4 is relatively smaller so as to implement the following leptogenesis, so the second term in M_e actually makes major contributions. In this simple scenario, the fermion masses are newly expressed as follows,

$$\begin{aligned}
M_L &= \frac{v_L^2}{v_R^2} M_R^*, \quad M_R = U_0 \text{diag}(M_{\nu_{R1}} = M_{\nu_{R2}}, M_{\nu_{R3}}) U_0^T, \quad U_0 = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & 0 & \sqrt{2} \\ -1 & \sqrt{3} & \sqrt{2} \\ -1 & -\sqrt{3} & \sqrt{2} \end{pmatrix}, \\
M_D &= U_D \text{diag}(m_{D1}, m_{D2}, m_{D3}) U_D^T, \quad M_u = U_u \text{diag}(m_u, m_c, m_t) U_u^T, \\
M'_d &= \frac{\lambda_6}{\lambda_5} M'_u + \frac{1}{16\pi^2} Y_3'^T \text{diag}(A_{11}, A_{22}, A_{33}) M'_D Y_3' = U_{CKM} \text{diag}(m_d, m_s, m_b) U_{CKM}^T, \\
M'_e &\approx \frac{1}{16\pi^2} Y_3' \text{diag}(C_{11}, C_{22}, C_{33}) M'_u Y_3'^T = U_e \text{diag}(m_e, m_\mu, m_\tau) U_e^T, \\
M'_{\nu_L} &= U_D^\dagger M_L U_D^* - M'_D U_D^T M_R^{-1} U_D M_D^T = U_e U_{MNS} \text{diag}(m_{\nu_{L1}}, m_{\nu_{L2}}, m_{\nu_{L3}}) U_{MNS}^T U_e^T, \\
Y_3' &= U_D^\dagger Y_3 U_u^* = 4\pi U_e \text{diag}\left(\sqrt{\frac{m_e}{C_{11}m_u}}, \sqrt{\frac{m_\mu}{C_{22}m_c}}, \sqrt{\frac{m_\tau}{C_{33}m_t}}\right), \tag{14}
\end{aligned}$$

where the superscript apostrophe means that the masses and couplings are in the new flavor basis. U_{CKM} and U_{MNS} are respectively the quark mixing matrix and the lepton one, which were defined in [14] and [15]. For all kinds of the unitary matrices, their mixing angles and CP -violating phases are parameterized by the standard form in particle data group [16]. The solution of Y_3' has directly been derived from the equation of M'_e . If the coupling with Y_3 is vanishing, then the quark mixing U_{CKM} will become an unit matrix, and the interrelations between the quark masses and the lepton ones are nothing. In (14), most of the mass and mixing parameters are fixed by the experimental data, the undetermined parameters include five mass parameters $M_{\nu_{R2}}, M_{\nu_{R3}}, m_{D1}, m_{D2}, m_{D3}$, two mixing matrices U_e, U_D , and three scalar sector parameters $v_R, \frac{\lambda_5}{\lambda_6}, M_{\phi_c}$, where M_{ϕ_c} is involved in $A_{\alpha\beta}$ and $C_{\alpha\beta}$. Now the difficulty of solving (14) is greatly reduced. In conclusion, all of the above contents are the theoretical framework of the model.

III. Leptogenesis

After the flavor symmetries are broken and the CP is violated below the scale v_F , the universe undergoes inflation and reheating. The reheating temperature can reach to

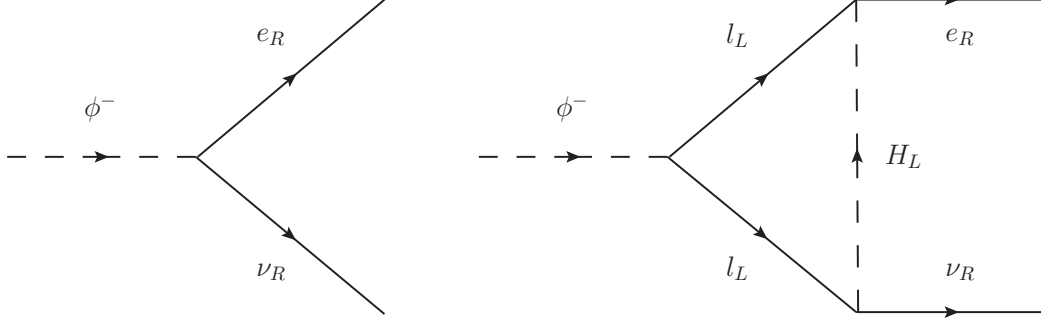


Figure. 3. The graphs of the decay $\phi^- \rightarrow e_R + \nu_R$ which leads to leptogenesis.

$T_{reheat} \sim 10^{13-14}$ GeV in some of the inflation models [17]. At this scale $\nu_R \sim T_{reheat}$ the $SU(2)_R \otimes U(1)_{B-L}$ gauge symmetry is broken and the left-right mirror symmetry is lost. As a result, the non-SM gauge and scalar bosons and the right-handed neutrinos ν_R obtain their masses. In virtue of the lepton number violation, ν_R become the Majorana neutrinos. As the universe expansion and cooling, the charged scalar ϕ^- can decay into $l_L + l_L$ or $e_R + \nu_R$. However, the decay $\phi^- \rightarrow e_R + \nu_R$ evidently violates two units of the lepton number. In view of the CP violation in the effective Yukawa couplings, a CP asymmetry of the decay process is generated through the interference between the tree diagram and the loop one, shown as figure 3. In addition, the ϕ^- decay is actually an out-of-equilibrium process for an enough small Y_4 , namely the decay rate is far smaller than the Hubble expansion rate of the universe,

$$\Gamma(\phi^- \rightarrow e_R + \nu_{Ri}) = \frac{M_{\phi^-} (Y_4 Y_4^\dagger)_{ii}}{16\pi} \ll H(T = M_{\phi^-}) = \frac{1.66\sqrt{g_*} M_{\phi^-}^2}{M_{pl}}, \quad (15)$$

where $M_{pl} = 1.22 \times 10^{19}$ GeV, and g_* is an effective number of relativistic degrees of freedom at $T = M_{\phi^-}$. At this temperature, the relativistic particles are exactly the SM ones, so one can easily figure out $g_* = 106.75$. In short, the decay $\phi^- \rightarrow e_R + \nu_R$ can satisfy three Sakharov's conditions [18], so the baryogenesis can be implemented through the leptogenesis in the model.

The decay CP asymmetry is defined and calculated as follow,

$$\varepsilon = \frac{\sum_i [\Gamma(\phi^- \rightarrow e_R + \nu_{Ri}) - \Gamma(\phi^+ \rightarrow \bar{e}_R + \bar{\nu}_{Ri})]}{\Gamma_{total}(\phi^-)} = \frac{Im[\sum_i (Y_D^T Y_4 Y_e Y_4^\dagger)_{ii} f_i]}{4\pi(Tr[Y_4 Y_4^\dagger] + \sum_i (Y_4 Y_4^\dagger)_{ii})}, \quad (16)$$

$$\Gamma_{total}(\phi^-) = \Gamma(\phi^- \rightarrow l_L + l_L) + \sum_i \Gamma(\phi^- \rightarrow e_R + \nu_{Ri}), \quad f_i = 1 - 2\frac{M_{\nu_{Ri}}^2}{M_{\phi^-}^2},$$

where the sum index i is limited by $M_{\nu_{Ri}} < M_{\phi^-}$. (16) clearly manifests that ε is closely related to the lepton CP violation, which is directly indicated by Y_D and Y_e . The size of ε is essentially dominated by Y_D and Y_e , while Y_4 has only little influence on it. However, (16) can naturally give a required value of ε , namely $\varepsilon \sim 10^{-8}$.

Below the scale v_R , the baryon number is conserved but the lepton number is violated, the above-mentioned decay process accordingly leads to the $B - L$ asymmetry in the universe. Afterwards, the $B - L$ asymmetry is partly converted into the baryon asymmetry through the sphaleron processes above the electroweak scale [19]. These results are expressed as follow,

$$Y_{B-L} = \frac{n_{B-L} - \bar{n}_{B-L}}{s} = \kappa \frac{(-2)\varepsilon}{g_*}, \quad Y_B = c_s Y_{B-L}, \quad \eta_B = \frac{n_B - \bar{n}_B}{n_\gamma} = 7.04 Y_B. \quad (17)$$

s is the entropy density. κ is a dilution factor, it can be approximated to $\kappa \approx 1$ for a very weak decay which is serious departure from thermal equilibrium. $c_s = \frac{28}{79}$ is a coefficient of the electroweak sphaleron conversion. 7.04 is a ratio of the entropy density s to the photon number density n_γ . Obviously, the value of η_B is completely determined by ε . Therefore, the present-day baryon asymmetry can be explained in the model very well.

IV. Numerical Results

In the section I present the model numerical results. The model involves a lot of the new parameters besides the SM ones. In principle the SM parameters are fixed by the experimental data, the non-SM parameters will be determined by solving the system of equation (14) and fitting the baryon asymmetry. In the light of the foregoing discussions, we can choose the below quantities of the SM as the input parameters (mass unit in GeV),

$$\begin{aligned} \sin\theta_W &= 0.231, & M_{Z_L} &= 91.2, & M_{H_L} &= 126, & v_L &= 246, \\ m_u &= 0.0023, & m_c &= 1.275, & m_t &= 173, \\ m_e &= 0.000511, & m_\mu &= 0.1057, & m_\tau &= 1.777. \end{aligned} \quad (18)$$

All of them come from the particle data group [16]. The non-SM parameters are input by the below values,

$$\begin{aligned} v_R &= 2 \times 10^{14} \text{ GeV}, & M_{\phi_c} &= 2 \times 10^{13} \text{ GeV}, & \frac{\lambda_5}{\lambda_6} &= 0.0242, \\ M_{\nu_{R1}} &= M_{\nu_{R2}} = 6.05 \times 10^{12} \text{ GeV}, & M_{\nu_{R3}} &= 3.55 \times 10^{13} \text{ GeV}, \\ (Y_{D1}, Y_{D2}, Y_{D3}) &= 0.0645 \times (0, -1, 1), \\ \sin\theta_{12}^e &= 0.058, & \sin\theta_{23}^e &= 0.66, & \sin\theta_{13}^e &= 0.0313, & \delta^e &= -0.48\pi, \\ \sin\theta_{12}^D &= \frac{1}{2}, & \sin\theta_{23}^D &= 0.805, & \sin\theta_{13}^D &= \frac{1}{\sqrt{2}}, & \delta^D &= 0.11\pi, \end{aligned} \quad (19)$$

where the last two lines are respectively the mixing angles and CP -violating phases in U_e and U_D . In (19), v_R and M_{ϕ_c} are actually taken as the fixed values. Firstly, the parameters, $\frac{\lambda_5}{\lambda_6}, Y_{D1}, Y_{D2}, Y_{D3}, U_e$, are determined by the equation of M'_d in (14). Secondly, the remaining parameters, $M_{\nu_{R1}}, M_{\nu_{R3}}, U_D$, are solved by the equation of M'_{ν_L} in (14). In this fitting, it is however found that (Y_{D1}, Y_{D2}, Y_{D3}) can be set as only one tuning

parameter and $\sin\theta_{12}^D = \frac{1}{2}, \sin\theta_{13}^D = \frac{1}{\sqrt{2}}$ can also be fixed. Therefore, the adjustable parameters in (19) are in fact ten in all. Of course, the parameter characteristics arise from the model theoretical structures.

Firstly, by use of (10) we can obtain the masses of the right-type gauge and scalar bosons (in GeV as unit),

$$M_{W_R} = 6.5 \times 10^{13}, \quad M_{Z_R} = 7.8 \times 10^{13}, \quad M_{H_R} = 1.02 \times 10^{14}. \quad (20)$$

They are mainly subject to v_R . However, these particles are too heavy and irrelevant to the present low-energy phenomenology.

Secondly, by use of (14) we can predict the down-type quark masses, the quark mixing U_{CKM} , the light neutrino masses, and the lepton mixing U_{MNS} . All kinds of results are given as follows,

$$\begin{aligned} m_d &= 4.9 \text{ MeV}, \quad m_s = 95 \text{ MeV}, \quad m_b = 4.18 \text{ GeV}, \\ \sin\theta_{12}^{ckm} &= 0.2252, \quad \sin\theta_{23}^{ckm} = 0.0415, \quad \sin\theta_{13}^{ckm} = 0.00352, \\ \delta^{ckm} &= -0.397\pi, \quad J_{cp}^{ckm} = -3.03 \times 10^{-5}, \\ m_{\nu_{L1}} &= 0.0079 \text{ eV}, \quad m_{\nu_{L2}} = 0.012 \text{ eV}, \quad m_{\nu_{L3}} = 0.05 \text{ eV}, \\ \Delta m_{21}^2 &= 7.5 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2, \\ \sin\theta_{12}^{mns} &= 0.552, \quad \sin\theta_{23}^{mns} = 0.707, \quad \sin\theta_{13}^{mns} = 0.156, \\ \delta^{mns} &= 0.975\pi, \quad J_{cp}^{mns} = 2.75 \times 10^{-3}, \quad \beta_1^{mns} = -0.53\pi, \quad \beta_2^{mns} = -0.5\pi, \end{aligned} \quad (21)$$

where J_{cp}^{ckm} and J_{cp}^{mns} are respectively the CP -violating Jarlskog invariants in the quark and lepton sectors, β_1^{mns} and β_2^{mns} are two Majorana phases in U_{MNS} . Obviously, all the results are very well in accordance with the current experimental data [16]. In particular, we can use the fewer parameters to predict the greater mass and mixing values, thus the model shows a large power of predictions. This success is of course owing to the correlations of the fermion mass matrices, which originate from the model symmetries and their breakings. (21) predicts that the lepton CP violation is relatively larger, so it will possibly be detected in near future.

Lastly, we also need input M_{ϕ^-} and Y_4 in order to calculate the baryon asymmetry. Their values are taken as

$$M_{\phi^-} = 9.3 \times 10^{12} \text{ GeV}, \quad Y_4 = 10^{-3}(T - T^T), \quad Y'_4 = U_D^\dagger Y_4 U_D^*, \quad (22)$$

where Y_4 is fixed and only M_{ϕ^-} is tuned to fit η_B . It should be noted that $M_{\nu_{R1}} = M_{\nu_{R2}} < M_{\phi^-} < M_{\nu_{R3}}$, so the sum in (16) is only for $i = 1, 2$. By use of (15)-(17), the out-of-equilibrium condition and the baryon asymmetry are calculated as

$$\frac{\Gamma(\phi^- \rightarrow e_R + \nu_{R1,2})}{H(T = M_{\phi^-})} = 0.0088, \quad \eta_B = 6.12 \times 10^{-10}. \quad (23)$$

The above first relation clearly demonstrates that the ϕ^- decay is indeed out-of-equilibrium. The value of η_B is precisely in agreement with the current data of the universe observations

[20]. In brief, all of the numerical results are naturally produced without any fine tuning. They not only correctly reproduce all kinds of the experimental data, but also give some predictions. This clearly demonstrates that the model is reasonable and feasible.

V. Conclusions

In this paper, I discuss the left-right symmetric model with the gauge groups $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ and the flavor symmetries $Z_{3L} \otimes Z_{3R}$. The model can account for the origin of the fermion masses and CP violation, and also implement the baryogenesis through the leptogenesis. At first, the flavor symmetries and the CP invariance are spontaneously broken by the flavor field developing the VEV, soon afterwards, the right-handed isospin and $B - L$ gauge subgroups are spontaneously breakings, and the left-right mirror symmetry is lost. It is these symmetries and their breakings that lead to the special effective Yukawa couplings at the low energy, which eventually generate the fermion masses and mixings. In the light of the model theoretical structures, the lepton and quark masses have common origin, namely all of them stem from the Majorana and Dirac masses of N_L and N_R , in particular, the Dirac coupling Y_{ND} is the only source of the flavor breaking and CP violation. As a result, the fermion mass matrices are not independent but rather there are the correlations among them. The model can naturally and correctly reproduce all kinds of masses and mixings of the SM and neutrino physics by the fewer parameters, so it shows a large power of predictions. In addition, the decay of the super-heavy scalar $\phi^- \rightarrow e_R + \nu_R$ satisfies the lepton number violation, the CP asymmetry, and being out-of-equilibrium. The CP asymmetry is directly related to the lepton CP violation. The generated lepton asymmetry is eventually converted into the baryon asymmetry through the sphaleron processes above the electroweak scale. All of the numerical results are in agreement with the experimental data very well. The model predicts the leptonic $J_{cp}^{mns} \approx 2.75 \times 10^{-3}$, it will possibly be detected in near future. Finally, the model is feasible and promising to be tested in future experiments.

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